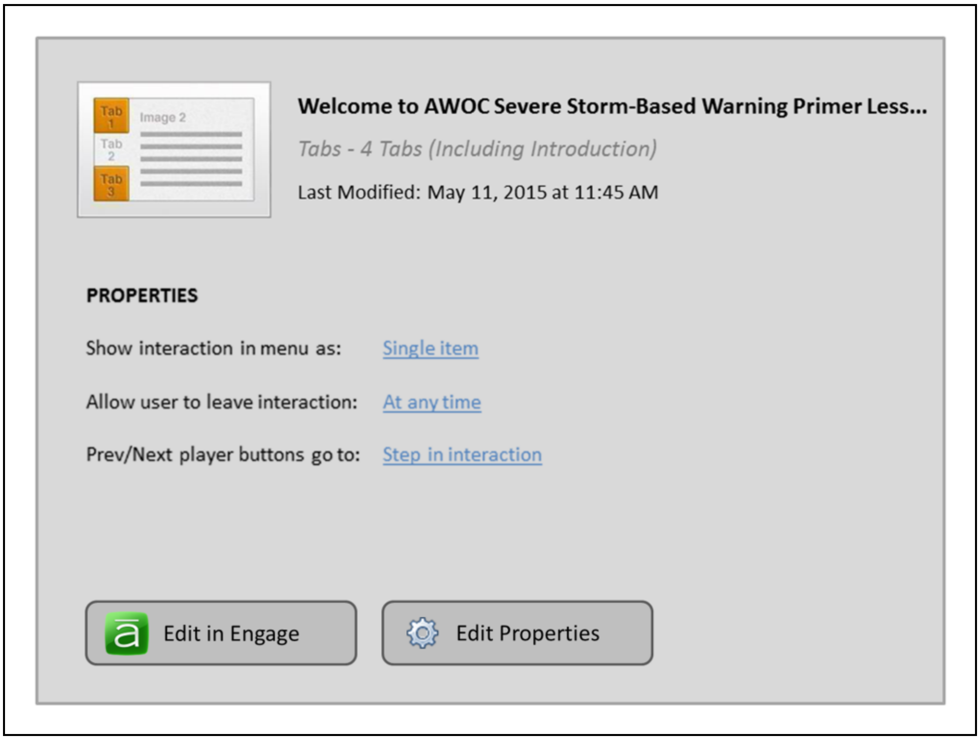
Welcome AWOC students. The title for this lesson is Conceptual Models for Supercell Tornadic Storms. This is the first lesson in Instructional Component 1 in the AWOC Severe Track. Lesson 1 will describe various conceptual models for supercell tornadic storms, including some of the more recent research from VORTEX 2. Our authors are me, Brad Grant and Les Lemon, from the Warning Decision Training Branch.


Tab 1
Tab 2
Tab 3
Image 2
Welcome to AWOC Severe Storm-Based Warning Primer Less...
Tabs - 4 Tabs (Including Introduction)
Last Modified: May 11, 2015 at 11:45 AM
PROPERTIES
Show interaction in menu as: Single item
Allow user to leave interaction: At any time
Prev/Next player buttons go to: Step in interaction
Edit in Engage
Edit Properties

Learning Objectives

Lesson 1 : Supercell Tornadic Storms

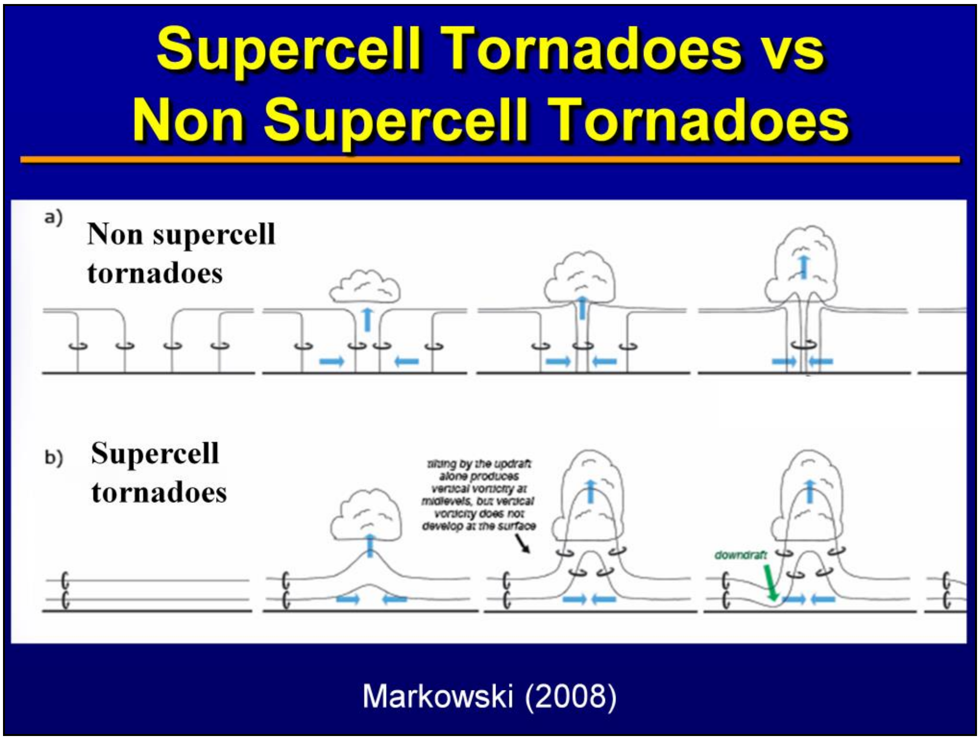
1. Identify the importance of forward flank baroclinic vorticity
2. Identify favorable storm-scale boundary characteristics which can enhance vertical vorticity
   - Through tilting
   - And stretching
3. Identify potential origins of storm-scale vorticity due to the rear-flank downdraft (RFD)
   - Downward-tilting of vortex lines along RFD surge
   - Baroclinic generation in the RFD (due to buoyancy effects)
   - Descending Reflectivity Core (DRC)
4. Identify the role of the RFD on tornado maintenance

These are the learning objectives for lesson 1: 1) Identify the importance of forward flank baroclinic vorticity, 2) Identify favorable storm-scale boundary characteristics which can enhance vertical vorticity through tilting and stretching, 3) Identify potential origins of storm-scale vorticity due to the rear-flank downdraft (RFD) such as downward-tilting of vortex lines along RFD surge, baroclinic generation in the RFD (due to buoyancy effects), or the Descending Reflectivity Core (DRC), and 4) Identify the role of the RFD on tornado maintenance.

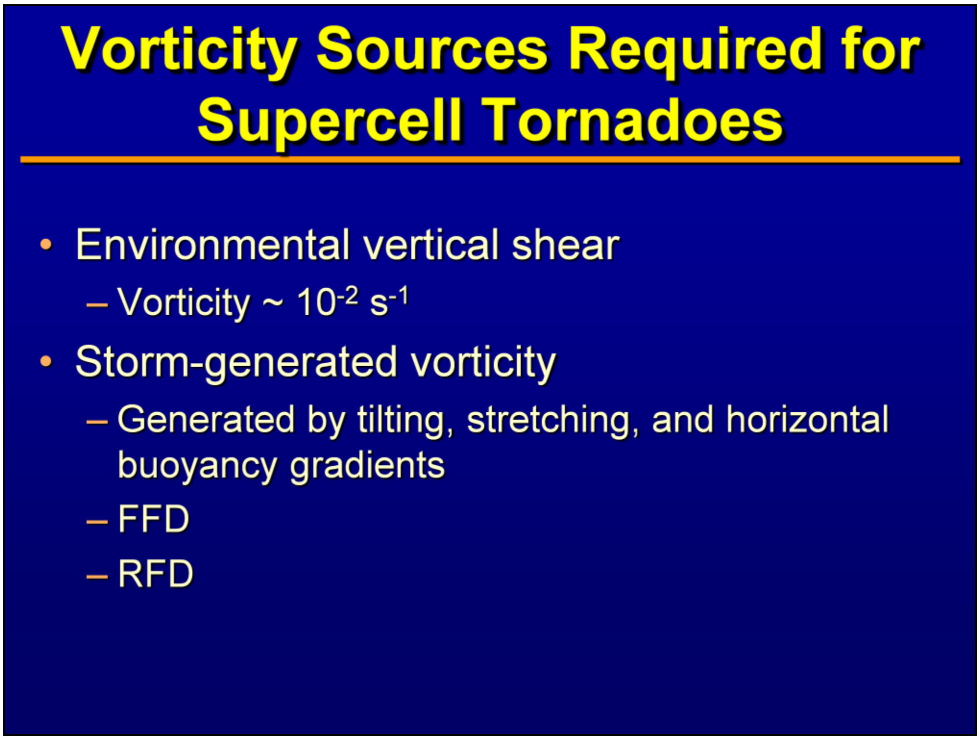
There will be a test on the learning objectives for this lesson.

According to Smith et al. (2012), nearly 90% of strong (EF2/3) and virtually all violent (EF4/5) tornadoes in the U.S. are spawned by right-moving supercell thunderstorms. Increased accessibility to advanced computer modeling, observations, and technology such as dual-pol radar have been used to study supercells more than ever before, enabling detailed scientific exploration of supercells and tornadoes, such as the Verification of the Origins of Rotation in Tornadoes Experiment (VORTEX 2), conducted in 2009-10.

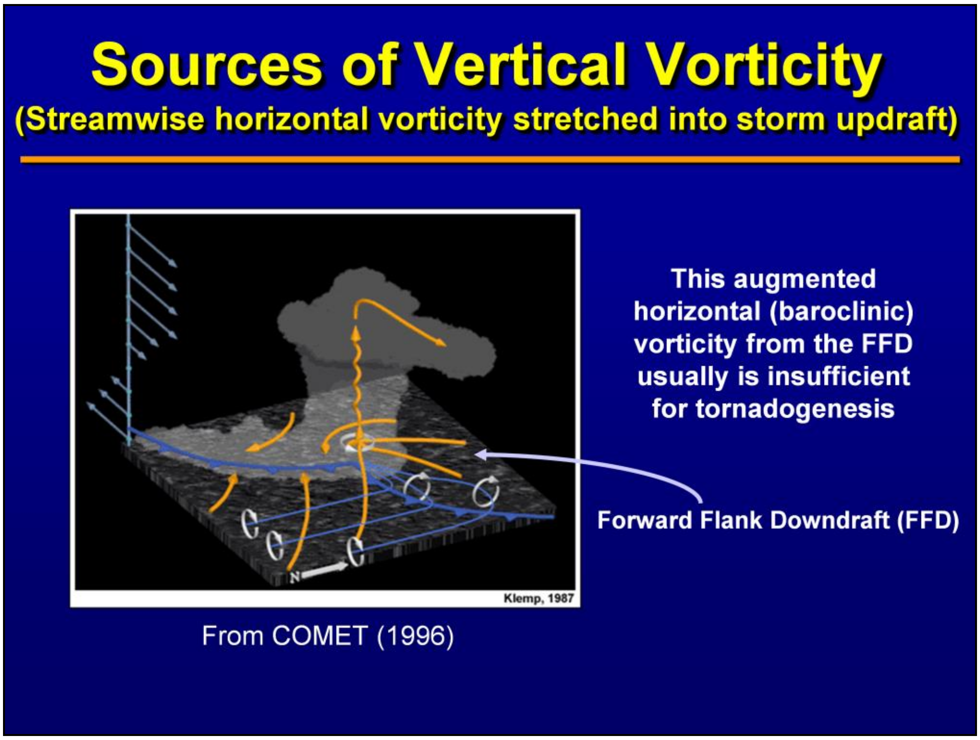
One of the goals of VORTEX 2, which was a successor to VORTEX 1 conducted back in the mid 90s, was to better understand the processes related to tornado formation, in particular, the wind, precipitation, and thermodynamic data and the local environment influential to the tornado life cycle. A better understanding of the tornado life cycle can help tornado warning accuracy, lead time, and false alarm rates. Results from VORTEX 2 are still being formulated but there has been a notable increase in the knowledge concerning the conceptual models of the processes governing tornadic storms. However, the findings have also accentuated gaps in our understanding of tornadogenesis, persistence, and demise. This module attempts to shed more light on supercell tornadoes based on observational evidence from VORTEX 1 and 2.



Tornadoes require a high concentration of vertical vorticity (vortex lines) embedded in converging and ascending flow into a convective updraft. The lines in the above figure containing a rotational symbol are “vortex lines” defined as a line that is everywhere tangent to the local vorticity vector. The basic structure shown in a) is that vertical vorticity is already embedded in a line of convergence and waiting for a locally intense updraft to intensify it through stretching. This type of tornado has been called a landspout, but is more appropriately, a non-mesocyclonic tornado. This type of tornado is the only kind that can occur in association with an ordinary cell updraft. The second type of tornado (b) is the type we will discuss in this lesson. They occur in an environment that has ambient horizontal vorticity that is tilted into vertical, which produces vertical vorticy in mid levels but not at the surface. In order to get a tornado in this situation. a downdraft must tilt vorticity into the vertical position at ground. An updraft cannot accomplish this by itself and so this tornado requires the existence of a downdraft. We call this a mesocyclonic tornado that can accompany supercells. Many tornadoes derive their vorticity from both sources but in disproportionate amounts.

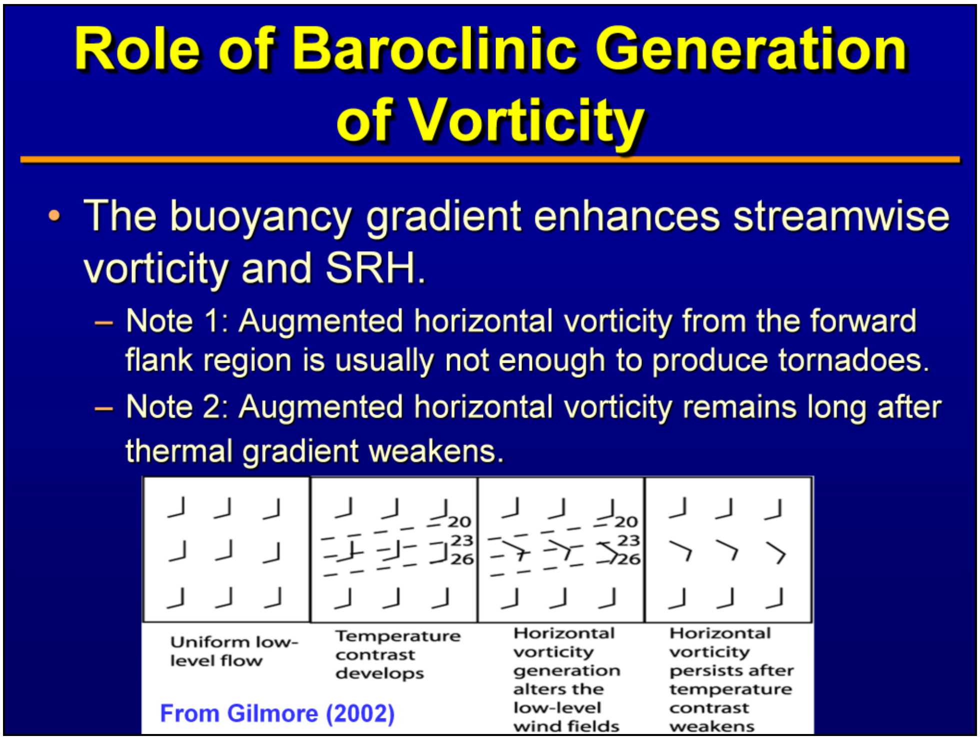


Environmental vorticity produced by shear is typically on the order of 10 to the -2 per second in the lower troposphere. In contrast, vorticity can be generated internally in supercell environments and can occur through a variety of ways, principally by horizontal buoyancy gradients (the so-called **baroclinicity** effects or sometimes correctly termed **baroclinity**), and the values are at least an order of magnitude larger than environmental vorticity.



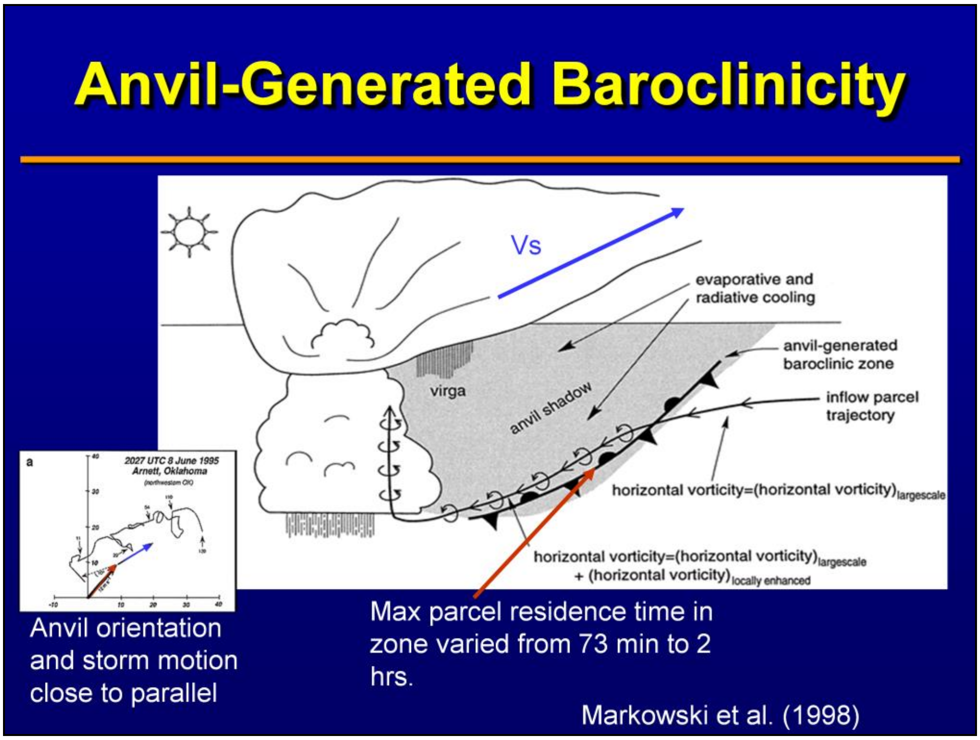
This 3-D figure from COMET (adapted from Klemp, 1987) depicts a classic supercell (absent the rear-flank downdraft (RFD) in its mature phase. The near-surface vortex lines (in blue) represent the environmental vorticity bending toward the storm's updraft in the forward flank baroclinic zone of the forward flank downdraft (FFD). This diagram, based on simulations in the mid to late 80s, indicates the baroclinic generation of horizontal vorticity in the FFD region. Once vorticity enters the updraft, it is tilted and stretched vertically to create much stronger low-level rotation. This process can be an important contributor to low-level storm rotation, which previously was thought to directly lead to tornadogenesis. However, more recent research suggested that augmented horizontal vorticity from the FFD was usually insufficient for tornadogenesis. In some storms there might not be a discernible FFD (thus no baroclinicity).

The low-level mesocyclone is now believed to arise from baroclinic affects generated along the RFD gust front. The RFD also produces vorticity via downward tilting of horizontal vorticity which also contributes to the low-level mesocyclogenesis. In rare cases where large-scale low-level horizontal vorticity is already very high (e.g., 0–3-km mean horizontal vorticity of $1 \times 10^{-2}\ s^{-1}$ or greater or storm-relative helicity of $500\ m^2\ s^2$ or greater), forward flank baroclinicity alone may provide sufficient augmentation of the horizontal vorticity associated with the large-scale low-level mean shear for tornadogenesis to occur.

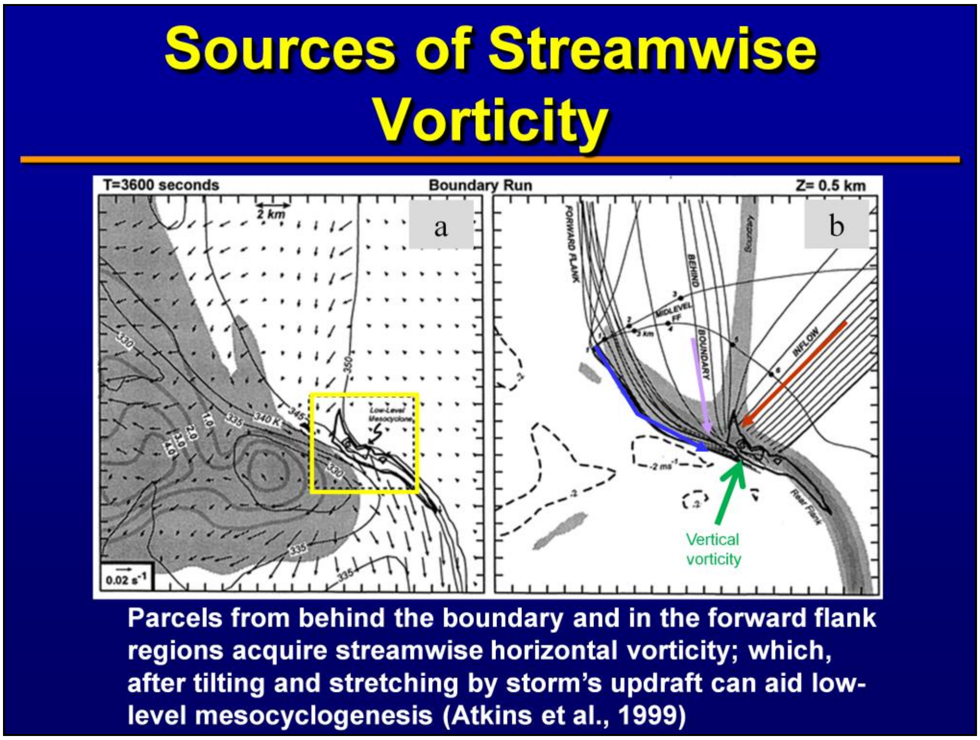


VORTEX 1 findings indicated that buoyancy gradients due to convective outflow and other mesoscale thermal boundaries generate baroclinic vorticity which can locally enhance the streamwise vorticity and storm-relative helicity (SRH). Thus, even though the horizontal baroclinic vorticity generated along a supercell's forward flank may be insufficient to support the low-level mesocyclonegenesis necessary for tornadoes, the addition of baroclinic vorticity from a pre-existing outflow boundary may be sufficient.

It is important to note that this baroclinically-generated horizontal vorticity remains long after the associated thermal gradient has weakened or dissipated. Numerous baroclinic vorticity zones associated with remnant boundaries could exist virtually undetected across the mesoscale landscape. That is why it is important to review radar reflectivity, storm total precipitation, and high-resolution visible satellite loops from several hours previously to help identify any remnant outflow boundaries.



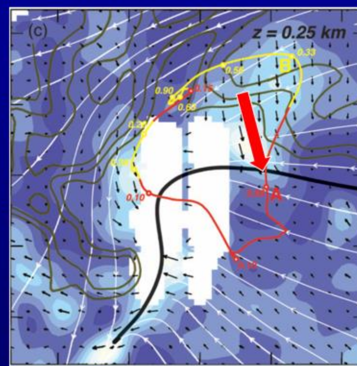
This is a conceptual model by Markowski et al. (1998) showing enhancement of low-level horizontal vorticity by an anvil-generated baroclinic zone. The amount of horizontal vorticity generated is a function of baroclinity and parcel residence time in the baroclinic zone. Residence time is a function of both storm-relative inflow speed and crossing angle with respect to the baroclinity. Horizontal vorticity will be mostly streamwise if the crossing angle of the storm relative near-surface inflow with respect to the anvil zone is very small (~ 0). The estimated maximum parcel residence time was around two hours for the three cases examined. Their research of proximity hodographs in baroclinic regions revealed that to maximize horizontal vorticity generation in the near-ground inflow, the head of the storm motion vector should lie close to the line drawn from the heads of the 0 to 500 mb mean wind vector and the wind vector near the equilibrium level. This assumes that the baroclinic zone is aligned closely with the anvil edge. Horizontal vorticity generated with a streamwise component can serve to enhance the storm-relative helicity already present in the environment due to the low-level vertical shear. SRH has been shown to be the source for net updraft rotation in supercells. Thus, the observations of anvil-generated baroclinicity had implications for the origin or enhancement of updraft rotation in thunderstorms.



The sources of streamwise vorticity in supercell thunderstorms are important to understand. Atkins et al. (1999) presented a case which explained the concept showing low-level storm structure (0.5 km AGL) at 1 hour for a boundary simulation and the source region for the low-level meso which is in the yellow square region. Parcels from behind the boundary and in the forward flank regions acquired a streamwise horizontal vorticity which, after tilting and stretching by storm's updraft, aided low-level mesocyclogenesis. Details for the diagram are given in the speaker notes. In the diagram (a), rainwater mixing ratio greater than 0.1 g kg^{-1} is shaded gray. The gray contours are rainwater mixing ratio starting at 1.0 g kg^{-1}. Thin black lines are θ_e (K). Thick black lines are vertical vorticity with contours starting at 0.01 s^{-1} and a contour interval of 0.01 s^{-1}. The vector field is horizontal vorticity. In diagram (b), positive and negative vertical velocities are gray shades and thick dashed lines, respectively. The contour and shade interval is 2 m s^{-1} . Thin solid lines are the projection of the 3D trajectory locations. I've drawn arrows to highlight the three principal trajectory projections, blue is the forward flank region, purple is the behind the boundary, and red arrow indicates the inflow region. Numbers at the black dots on the midlevel trajectories are the height of the parcel (AGL). Thick solid lines are vertical vorticity. Note that the preexisting boundary provides an important additional source region of parcels at low levels that have acquired solenoidally generated streamwise vorticity. The next slide shows a slightly different result from VORTEX 2.

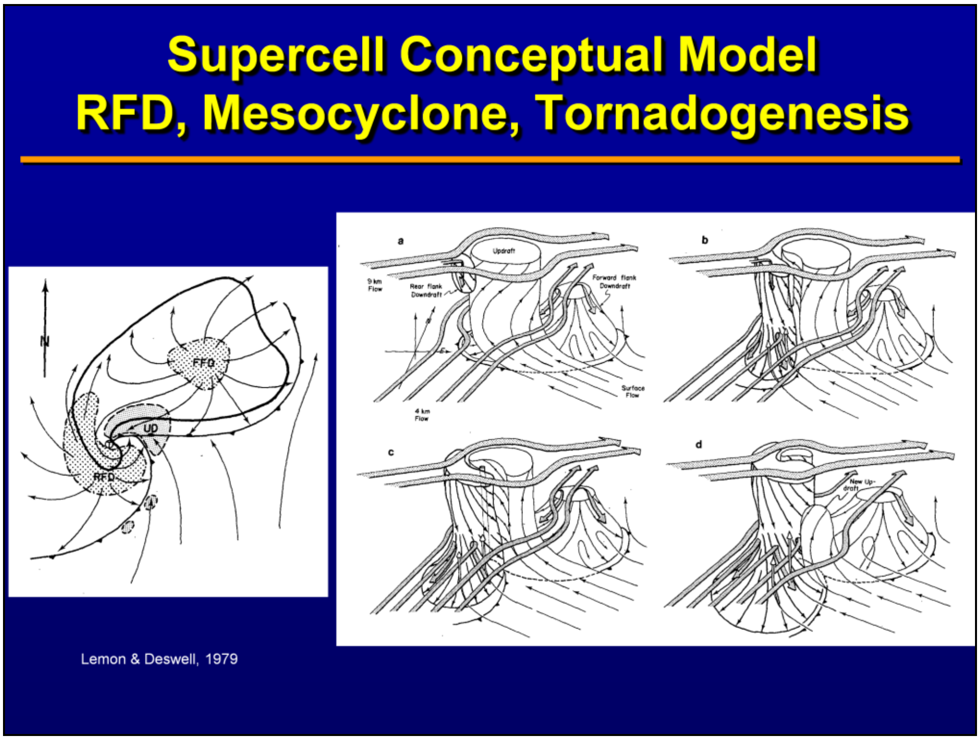
Is All Horizontal Vorticity in the Forward Flank Region Streamwise?

- Some baroclinic generated vorticity in Goshen, WY VORTEX 2 storm was oriented crosswise at low-levels



From Markowski et al (2012)

VORTEX 2 findings suggested baroclinically generated vorticity below .75 km was crosswise (vector pointed across the thermal gradient), which is at odds in previous numerical simulations. It might have been influenced by surface drag. However, they did find more streamwise vorticity at Z=.75 km and above. Moreover, significant portions of the low-level radar velocity fields were contaminated by ground clutter and were censored.



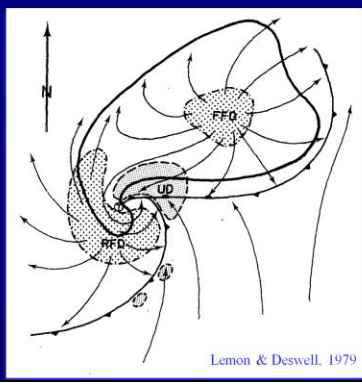
Hi, this is Les Lemon.

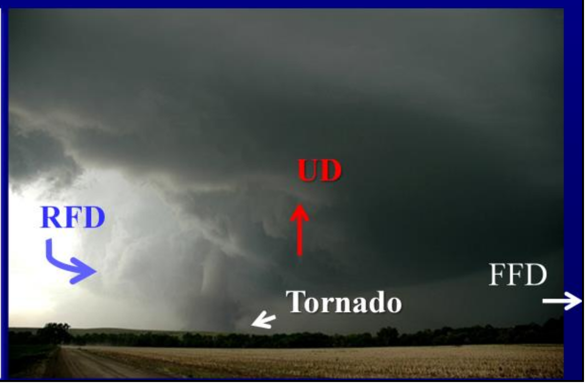
The purpose of this supercell schematic and the material to come in this lesson is designed to inform the student of our present day understanding of the supercell as well as how it relates to warning issuance and radar detection. This conceptual supercell model was introduced in 1979 but is still largely current today. On the left is the schematic plan view of a supercell storm at the surface. Relevant details will be covered in the next slides.

On the right, is the associated schematic depiction of the drafts, flow field, mesocyclone, and tornado within an evolving supercell (precipitation echo is omitted). Major features are labeled including storm relative flow in low-, mid-, and upper-levels throughout. Tornado is seen developing aloft in b) and over the full depth in c). While the RFD is seen as originating at ~ 9 km AGL that is still uncertain. The RFD is conceptualized more as a zone of flow decent where air parcels flow into the RFD while maintaining horizontal momentum, flow across the downdraft while descending, and flow out of the RFD where parcels mix with adjacent updraft. Note that the mesocyclone is seen as having a “divided structure” over the lower ½ to 2/3rds of storm depth similar to an extra-tropical cyclone (ETC). Storm relative, the mesocyclone updraft and storm inflow are on the left similar to the ETC “warm sector”, on the right is the downdraft (RFD) and outflow. Tornadogenesis takes place at the updraft-downdraft (RFD) interface but just inside the updraft. Note the “Forward Flank Downdraft” (FFD) is typical of all thunderstorms and is found in the precipitation cascade region. The RFD is unique to the supercell and is critical to tornadogenesis. The RFD is seen to flow or migrate around the circulation center (tornado location) as the RFD gust front “occludes”. A new updraft is shown in d) originating at the occlusion and may cycle through the process again becoming a cyclic tornado producer.

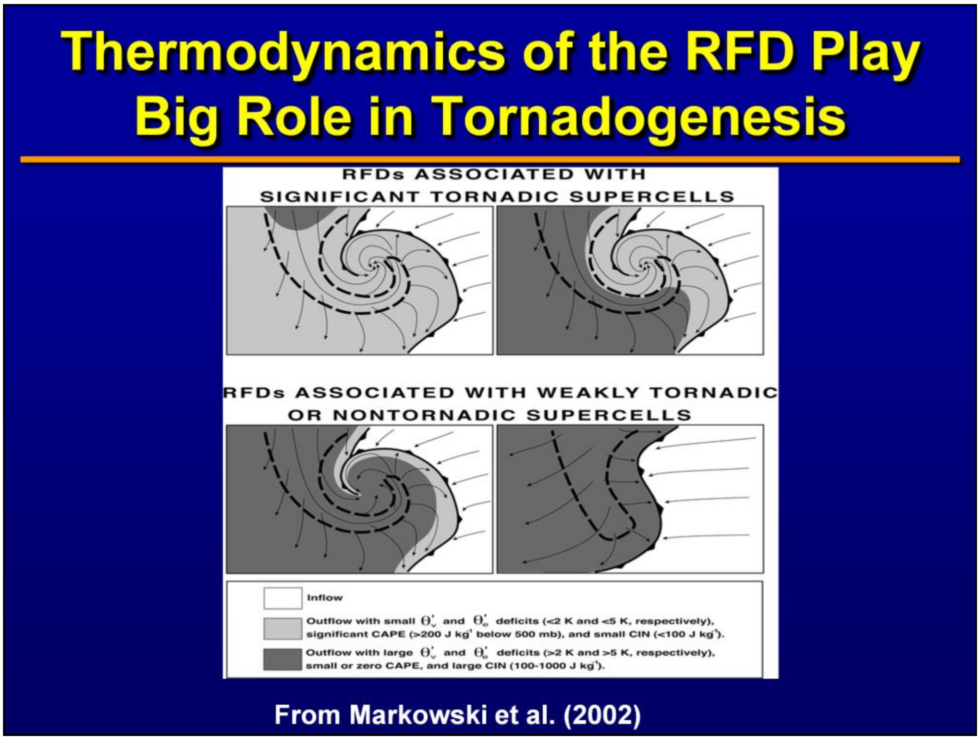
The Role of the RFD

- Important factor in tornadogenesis process for supercells

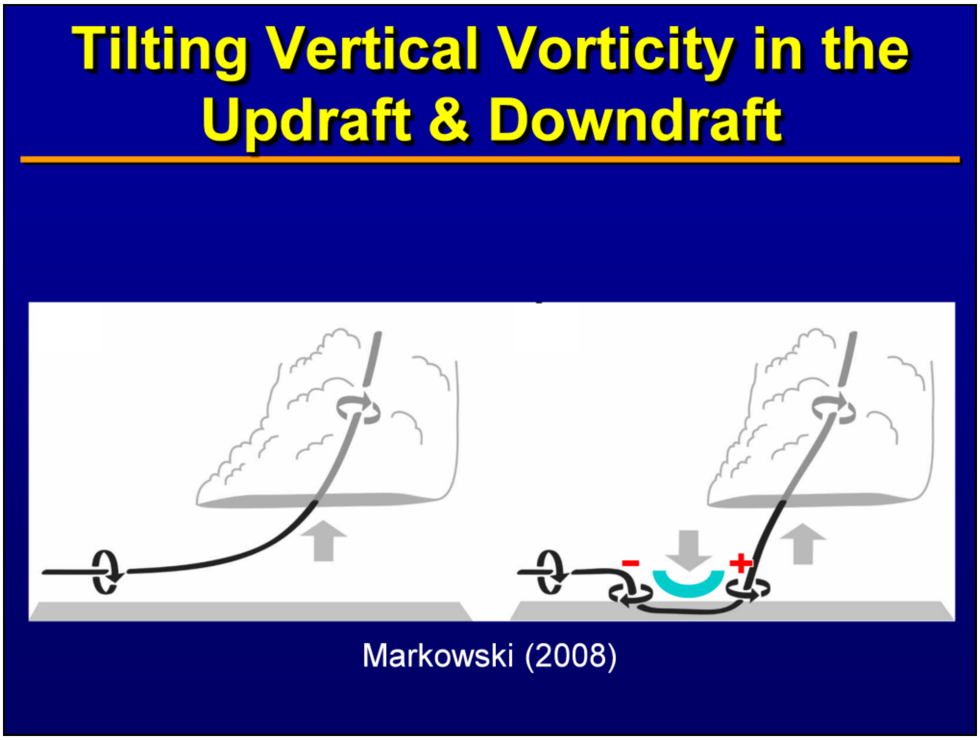




This schematic and photo tie the storm structure to the visual cloud and tornado locations. (After Lemon and Deswell, 1979) As in the previous slide, the thick line encompasses the radar echo. The gust front structure and occluding wave are depicted with solid lines and frontal symbols. Updraft (UD) and (Rear Flank Downdraft, RFD; and Forward Flank Downdraft, FFD) are included along with streamlines (surface relative). Tornado location is the encircled T. The photo on the right is taken from east southeast of the tornado, ahead of the RFD gust front and clearly shows the sunlit "clear slot" behind the bowing and occluding RFD gust front. Also seen in the photo is the dark, "horseshoe shaped" rain free cloud-base ahead of the wrapping RFD and is the major storm updraft. The tornado is seen in the distance located at the updraft/RFD downdraft interface.

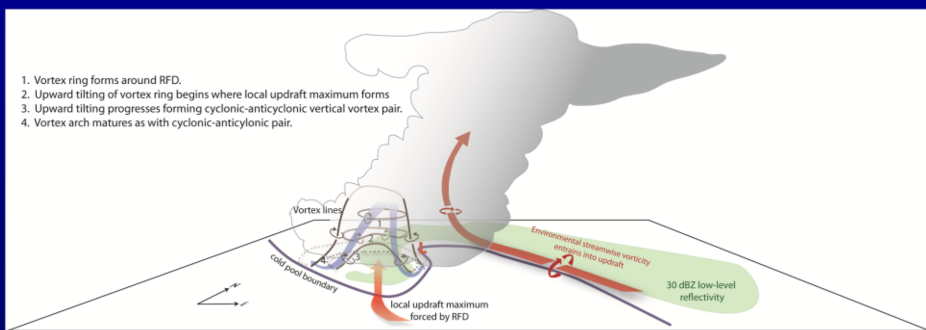


Markowski et al. (2002), developed this composite diagram illustrating the general characteristics of RFDs and their role in tornadogenesis. RFDs associated with supercells that produce “significant” (e.g., EF2 or stronger, or EF0–EF1 tornadoes persisting for >5 min) are shown in the upper two diagrams. RFDs associated with non-tornadic supercells or those that produce weak, brief tornadoes are shown in the lower diagrams. The thick, dashed contour is the outline of the hook echo, and thin, solid arrows represent idealized streamlines. Again, the bottom two depictions illustrate tornadogenesis failures. In cases where the RFD is characterized with only small theta-e deficits, small CIN, and significant potential CAPE, significant tornadoes often result. But when the dominant RFD outflow is characterized by large theta-e deficits and little potential CAPE, tornado genesis failures or only weak, short-lived tornadoes result as in the lower two frames. Note the above processes can arise with new RFD Internal Surges (RFDIS) that can sustain or end the life of associated tornadoes [Lee et al., 2012; Marquis, et al., 2012)]



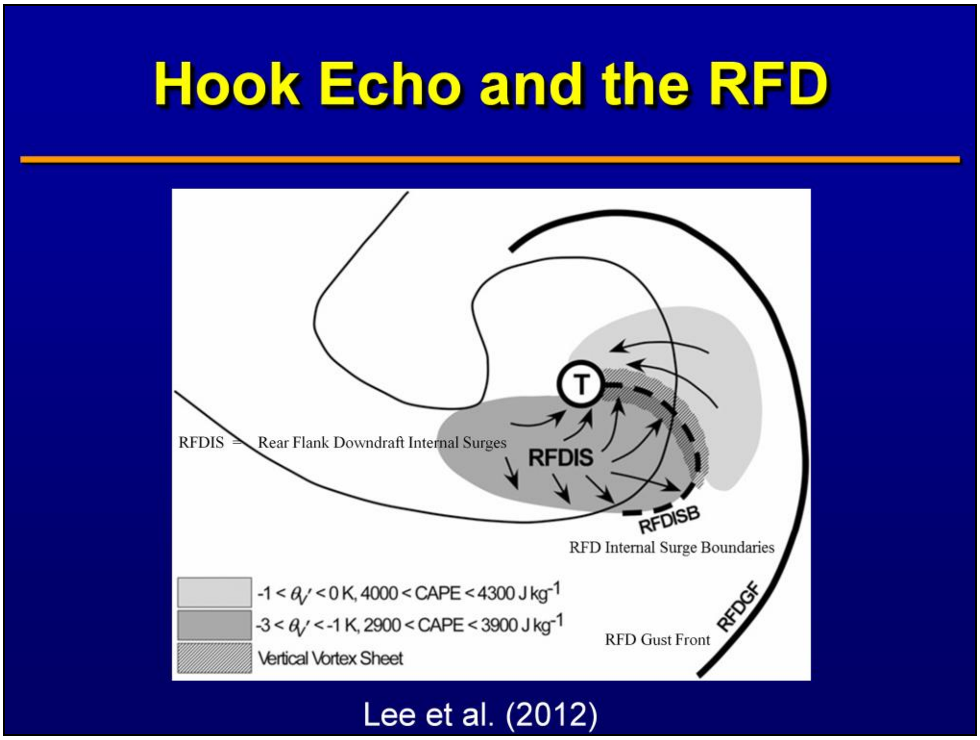
Here's an illustration showing the development of vorticity in both updraft and downdraft. Vertical vorticity and the mid-level mesocyclone has long been known to originate from the tilting of environmental horizontal vortex lines into the vertical and subsequent vertical stretching in the developing supercell updraft. However, the downward tilting of vortex lines in the RFD resulting in the low-level mesocyclone is of more recent understanding [e.g., Markowski, et al. (2008)]. This results in significant vertical vorticity next to the ground and the low-level mesocyclone. If baroclinity is absent (and turbulent diffusion is neglected), vortex lines are frozen in the fluid and are redistributed by the downdraft as material lines. In this case, the vortex line passing through the low-level vertical vorticity maximum and takes on a U shape rather than an arch. A couplet of counter-rotating vortices straddles the downdraft maximum and often the hook echo. When this and baroclinic vorticity generated from the RFD are converged and stretched, within the updraft, tornadogenesis may result.

Latest Research on the Role of RFDs and Tornadogenesis



Adapted from Markowski et al. (2012)

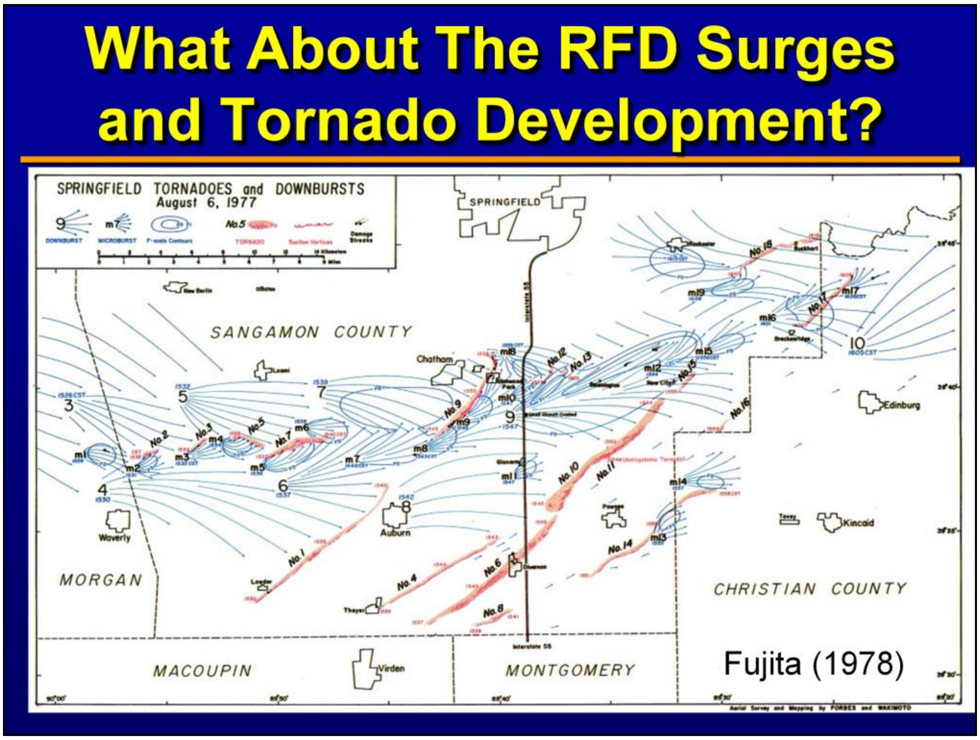
VORTEX 2 observations reveal the development of arching vortex lines that join counter rotating vortices found to be straddling the hook echo. But this is similar to what had been seen before in VORTEX 1 and thought to suggest significant baroclinic vorticity generation. So, as a horizontal vortex ring forms around the RFD, the upward tilting of the ring begins where the local updraft maximum forms. Upward tilting then progresses forming a cyclonic-anticyclonic vertical vortex pair. The vortex arch matures as does the cyclonic-anticyclonic pair. In some instances a cyclonic tornado arises within the hook with the mesocyclone while an anti-cyclonic tornado arises to the rear of the hook echo at the other end of the vortex arch. Note that you may detect some hook echoes via your radar that actually reveal the counter rotating vortices. Note also that counter rotating tornadoes can actually arise in the hook echo region.



This hook echo schematic summarizes some very recent and fascinating findings of Lee et al. (2012). They studied several tornadoes via a mobile mesonet and this model summarizes observations made very near a large EF-4 tornado that occurred near Bowdle, SD. Embedded within the larger supercell RFDs they sometimes found "RFD Internal Surges" (RFDIS) and "RFDIS Boundaries" (RFDISB). These features are thought to contribute to tornadogenesis, maintenance, and demise through their thermodynamic and kinematic character.

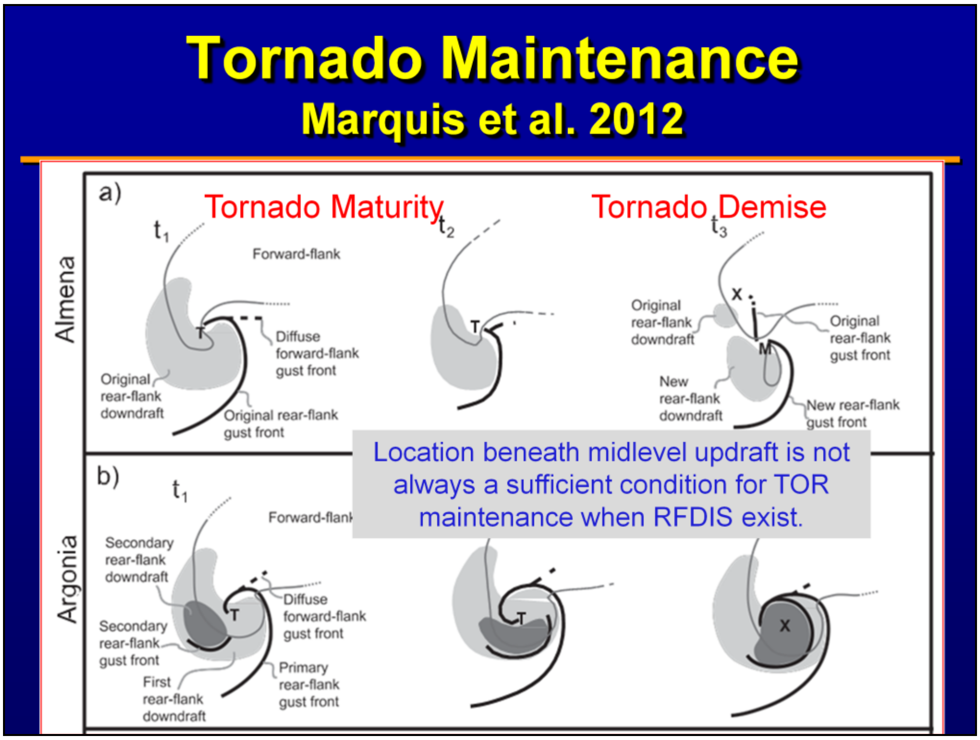
RFDISs with relatively strong kinematics and near neutral buoyancy that converge with very large potential buoyancy ahead of the RFDIS boundary contribute to tornado development and intensification. However, they also found RFDISs with weak kinematics and colder thermodynamics relative to the ambient RFDIS boundary air contributed to tornadogenesis failure or demise.

A lot going on here, but from the Bowdle, SD study we see a hook echo tip region behind the leading RFD Gust Front (RFDGF) during the rapid intensification stage of the tornado. The Bowdle tornado intensification stage may represent an optimal situation combining three processes: 1) RFD thermodynamics with just enough negative buoyancy for baroclinic vorticity generation (in this case the baroclinicity was provided by an RFDIS); 2) an augmented Tornado Cyclone convergence zone (denoted by the stippled vertical vortex sheet) due to the RFDIS and RFDISB interactions with the developing tornadic vortex; and 3) near-neutrally buoyant and very potentially buoyant air converging on the left flank of the tornado.

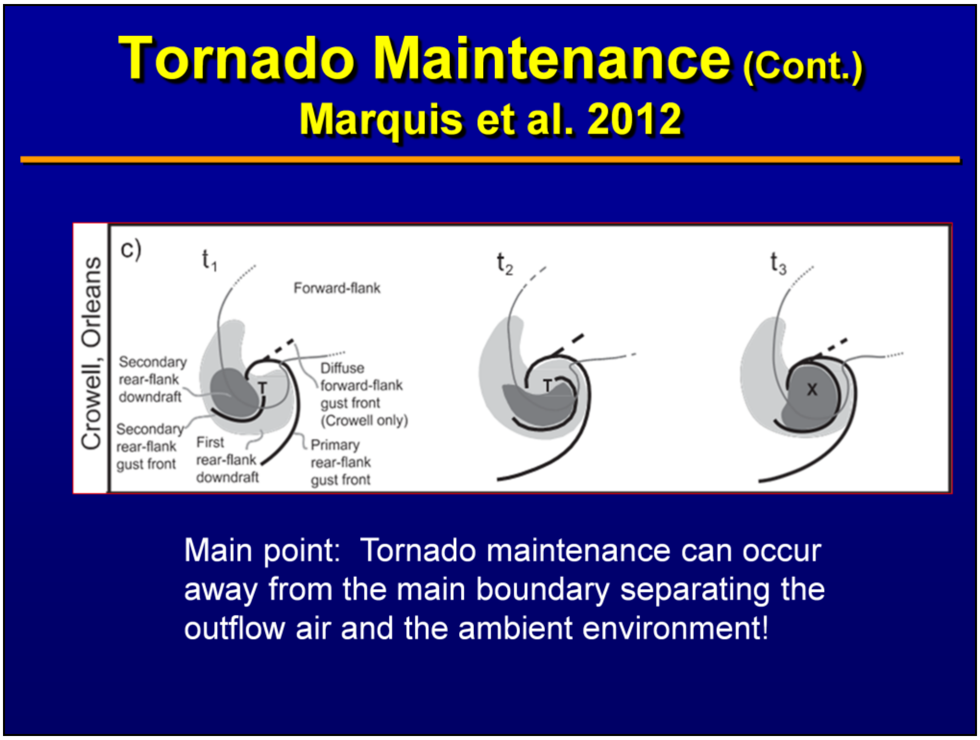


Fujita (1978) utilized his unprecedented care and detail to describe the relationship between tornadoes and downbursts from his storm damage survey of the Springfield, Illinois event of August 6, 1977. Eighteen tornadoes, 10 downbursts, and 17 microbursts are depicted in this map. Apparently, eight tornadoes formed on the left side of microbursts. No traces of downbursts were found in the vicinity of other tornadoes. Fujita documented very similar relationships in association with many other tornadoes. It is very likely that these microbursts and downbursts were "RFD Internal Surges". Recall the supercell schematic surface depiction and photo previously showing the tornado to the left of the RFD and "clear slot".

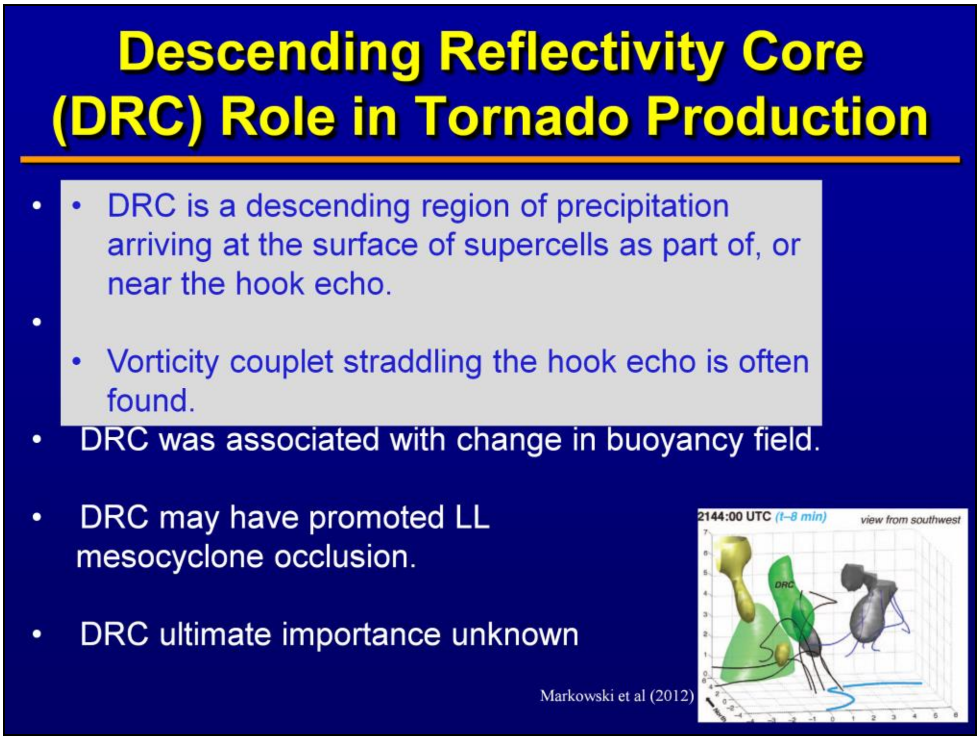
(NWS meteorologists, when doing storm damage surveys, should be aware of these downbursts and microbursts associated with these damaging RFDIS and include them where appropriate.)



Seen here is a schematic illustration of the evolution of storm-scale features located on the rear-flank of specific supercell storms during tornado maturity (t1 to t2) and at the time of demise (t3) in (a) the Almena storm and (b) the Argonia storm. t2 represents a time immediately before a rapid decline in tornado intensity. "T" marks the location of the tornado, "X" marks the location of tornado demise at t3, and "M" marks the location of mesocyclogenesis in the Almena storm at t3. Black lines indicate the presence of kinematic gust front boundaries, gray shades indicate varying magnitudes of low-level divergence associated with the rear-flank downdraft, and gray contours indicate radar reflectivity. Fine dashed lines indicate that the feature continues beyond the area shown. Long dashed lines indicate uncertainty in the location of the feature. In (a), the longest-lived tornado is maintained underneath the mid-level updraft within a zone of low-level horizontal convergence along a rear-flank gust front for a considerable time, and dissipates when horizontally displaced from the mid-level updraft. In (b) the shortest-lived tornado resides in a similar zone of low-level convergence briefly, but dissipates underneath the location of the mid-level updraft when the updraft becomes tilted and low-level convergence is displaced several kilometers from the tornado. This suggests that a location beneath the midlevel updraft is not always a sufficient condition for tornado maintenance, particularly in the presence of strongly surging outflow.



For two other storms in the Marquis et al. (2012) study, Crowell and Orleans, tornadoes persisted within a band of low-level convergence in the outflow air, not along a RFD Internal Surge Boundary, which suggests that tornado maintenance can occur away from the main boundary separating the outflow air and the ambient environment.



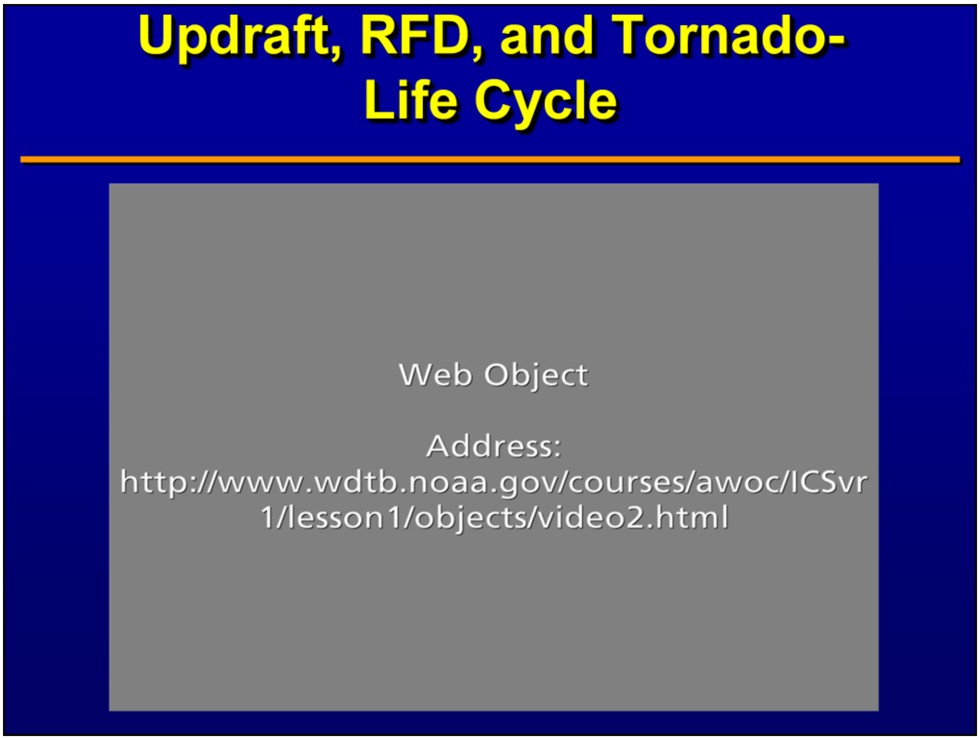
The descending reflectivity core (DRC) is a descending region of precipitation arriving at the surface of some supercells as part of, or very near the hook echo. When a DRC develops, a vorticity couplet straddling the feature is often found. However, whereas earlier studies of this feature seemed to implicate it's importance to low-level tornadogenesis, other studies have not upheld that observation. Tornadogenesis occurred in those studies with or without this feature. In Markowski et al (2012), a DRC was found in the VORTEX 2 Goshen County, Wyoming tornadic supercell to have some seemingly minor importance in altering the mesocyclone circulation and buoyancy fields. This, in turn, appears to promote the low-level mesocyclone occlusion. However, this VORTEX 2 study failed to establish a real importance to the DRC. Much more study is needed.

Video Illustrating RFD Importance to Tornadogenesis and Decay

Web Object

Address:
http://www.wdtb.noaa.gov/courses/awoc/ICSvr1/lesson1/objects/video1.html

This video time lapse by Neal Rassmussen in 2002 illustrates the importance of the RFD to tornadogenesis and demise. It begins with the updraft portion of a supercell's mesocyclone as seen at cloud base, followed by the development of an RFD (note the rain shaft with strong outflow and "rainfoot" just to the rear of the wall cloud), subsequent tornadogenesis, followed by mesocyclone occlusion, and finally, vortex dissipation as rain and outflow surround and engulf the rapidly dissipating vortex. This video clip will play continuously until the slide is advanced.



Here we zoom into the tornado as the strong outrush and RFD initiate the tornado, surround the vortex and lead to its demise. Note the strong divergence to the rear of the funnel/tornado and the descending cloud fragments to your left and the tornado's right flank. Note also that the descending precipitation is being "driven" or "forced" downward to the surface by the RFD in which the rain is embedded.

Relative Roles of FFD and RFD

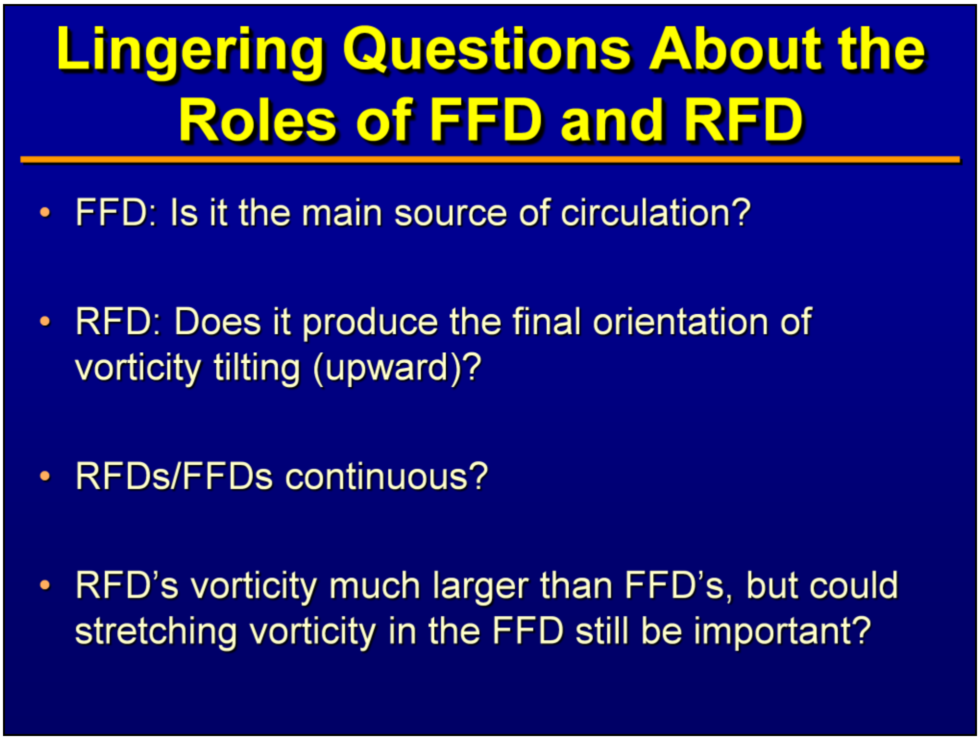
FFD	RFD
1. Provides baroclinic streamwise horizontal vorticity which is then tilted into vertical and helps to create the low-level mesocyclone.	1. Contributes to low-level horizontal baroclinic vorticity generation, tilted vertically, positive potential CAPE, and maximum stretching.
2. Insufficient alone for tornadogenesis.	2. RFD surges and boundaries can and do control genesis, sustenance, and tornado decay.
3. Contributes substantial circulation, and tornadic inflow.	3. Contributes to tornadic inflow.

Both are important for tornadogenesis, sustenance, and demise

Both the forward flank downdraft (FFD) and rear flank downdraft (RFD) play important roles in tornadogenesis, sustenance, and demise. The FFD provides baroclinic streamwise horizontal vorticity along the forward flank baroclinic zone which in turn is tilted and stretched. This helps to create the low-level mesocyclone and, at times, the tornado as well. However, this alone appears to be insufficient for tornadogenesis. The FFD also contributes substantially to mesocyclone circulation and tornadic inflow.

The RFD contributes to low-level baroclinic horizontal vorticity generation along its rear flank gust front which is turned into the vertical and converges rapidly into the updraft and developing tornado. Further, high potential CAPE associated with both the RFD and RFDIS is ingested by the tornado vortex and stretched. But, because the RFD is often weakly negatively buoyant (contributing to baroclinic vorticity generation) it requires a vertically directed pressure gradient force (VDPGF) to forcibly lift it to its level of free convection (LFC). Once reaching its LFC, that now buoyant air is rapidly accelerates vertically and is stretched, amplifying its vertical vorticity.

Interestingly, in the VORTEX 2 Goshen County case only about 1/4th of the tornadic vorticity arose from the near-storm environment, but 3/4ths were generated by the storm itself. However, at this point we can only say with confidence that both the RFD and the FFD are important to tornadogenesis, sustenance, and demise. (Note: A good article describing these roles is at http://journals.ametsoc.org/doi/pdf/10.1175/MWR-D-11-00337.1).



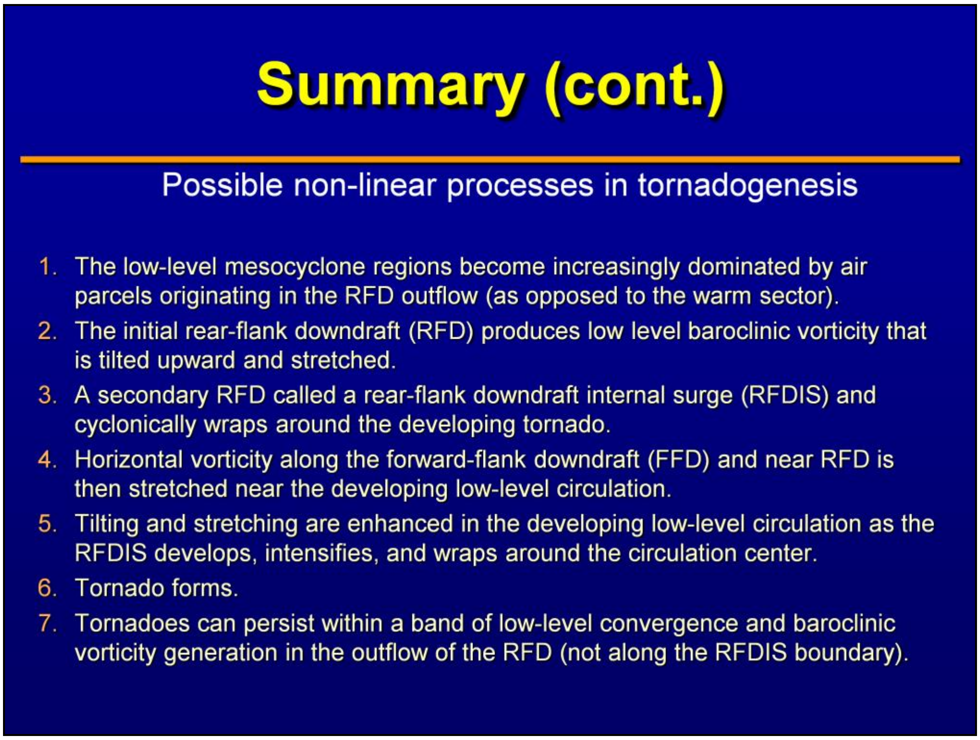
So, perhaps the FFD should be viewed as the main source of circulation, with the RFD being responsible for the rapid descent of the "rear" circulation circuits that allows them to become horizontal at their "final" positions about 4 minutes prior to tornadogenesis. Alternatively, perhaps distinguishing between RFDs and FFDs is no longer fruitful, given that the RFD and FFD may typically occur within one large, contiguous region of downdraft, and sometimes there may not even be two distinct downdraft maxima. Obviously, the relative roles of the FFD and the RFD have yet to be satisfactorily resolved. On the one hand, the RFD seems to be more relevant to the tornadogenesis process than the FFD because the RFD has vertical velocities an order of magnitude larger than the FFD and is associated with even larger horizontal gradients of vertical velocity (and therefore much larger vorticity tilting rates) given its closer proximity to the storm updraft. It also contributes to baroclinic generated vorticity for both mesocyclone and tornadogenesis. But, the researchers in VORTEX 2 felt that they couldn't dismiss the possibility of the process occurring within the gentle descent of the FFD. The development of only a small vertical vorticity component could be important given the subsequent exponential intensification possible from stretching.

Summary

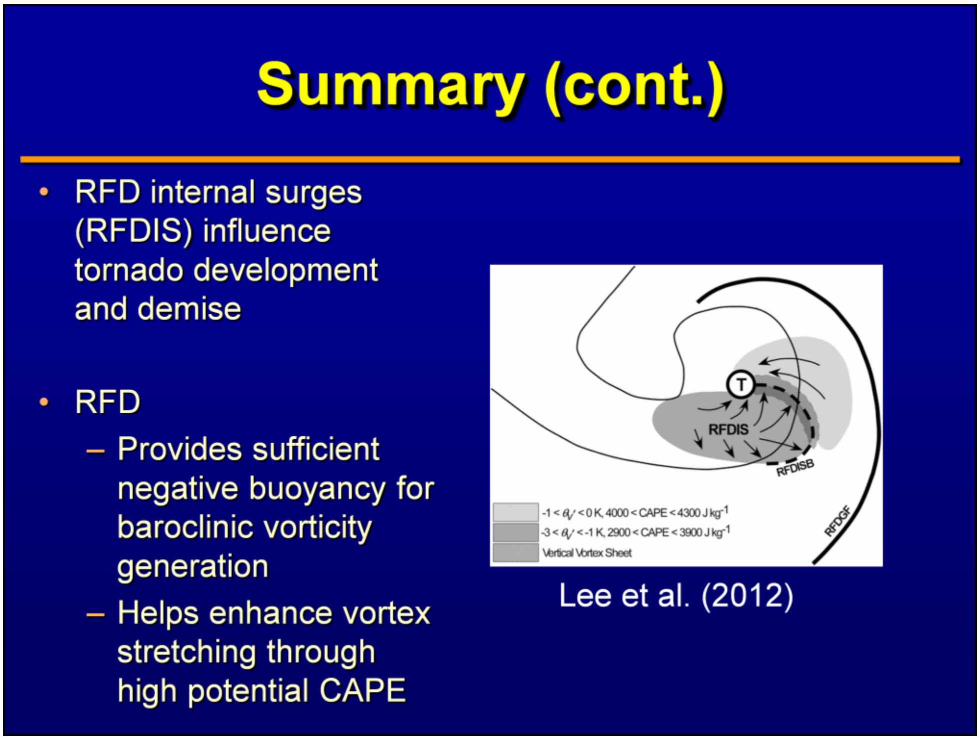
- Vorticity generated from environment is relevant (for tilting and stretching)
  - Environmental vorticity is essential for developing mid-level mesocyclone but not low-level mesocyclone
- Analysis in V2 suggests that storm-generated vorticity is a dominant contributor to the circulation of the low-level mesocyclone and tornado

In summary, vorticity generated from the environment is relevant (for tilting and stretching). Environmental vorticity is also essential for developing the mid-level mesocyclone, but not in low-levels.

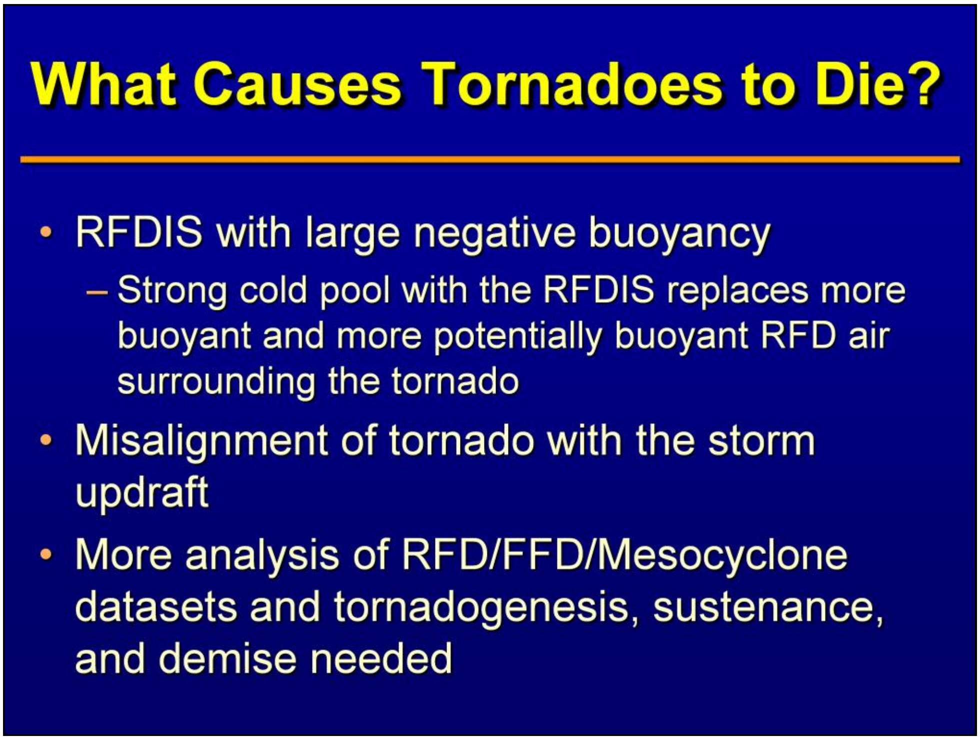
Analysis from VORTEX 2 suggests that storm-generated vorticity is a dominant contributor to the circulation and vorticity of the low-level mesocyclone.



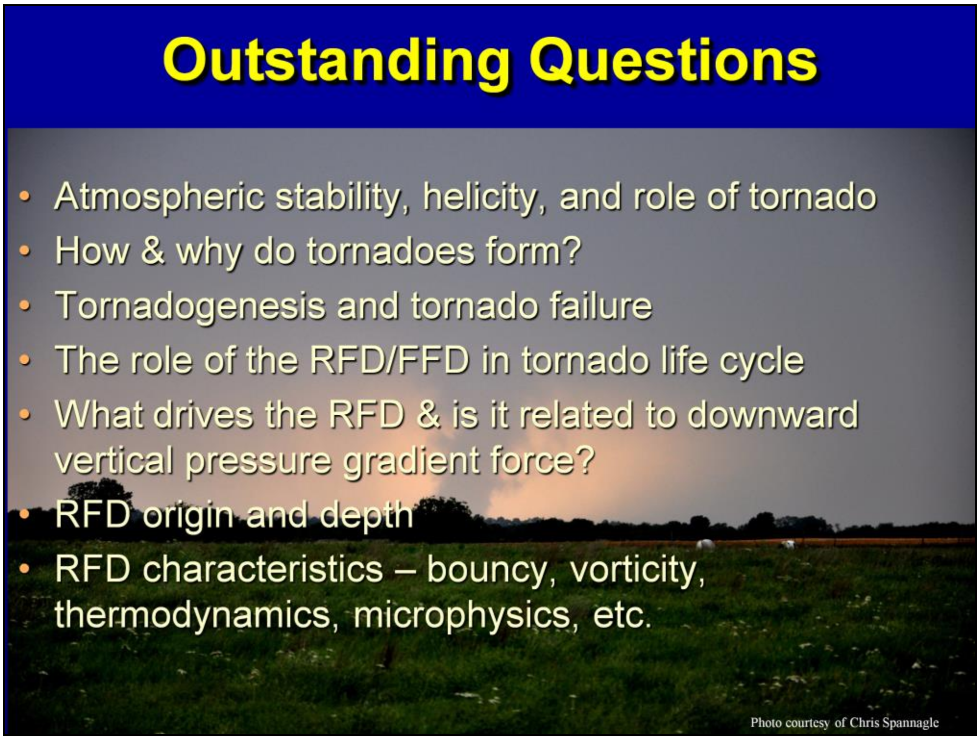
1) The low-level mesocyclone region is increasingly dominated by air parcels originating in the outflow (as opposed to the warm sector). 2) The initial rear-flank downdraft produces low level baroclinic vorticity that is tilted upward and stretched. 3) A secondary RFD forms (called the RFDIS) cyclonically wraps around the developing tornado cyclone region. 4) Horizontal vorticity created in the forward-flank downdraft region and near the RFD region near the hook echo is tilted and then stretched near the developing tornado. 5) Tilting and stretching are enhanced in the developing low-level circulation as the RFDIS develops, intensifies, and wraps around the circulation center. 6) Shortly thereafter, the tornado forms. 7) The tornadic circulation can persist within a band of low-level convergence in the RFD outflow air, not along the RFDIS boundary. Once again, this suggests that tornado maintenance can occur away from the main boundary separating the outflow air and the ambient environment.



RFD internal surge events appear to influence tornado development, intensity, and demise by altering the thermodynamic and kinematic character of the RFD. Significant tornadoes develop and mature when the RFD, modulated by internal surges, is kinematically strong, only weakly negatively buoyant, and very potentially buoyant. The influx of near-neutrally buoyant air with very large potential buoyancy may aid tornado intensification via enhanced vortex stretching. In contrast, the demise of the tornado intercepted by Lee et al., (Bowdle storm) was concurrent with a much cooler RFDIS that replaced more buoyant and far more potentially buoyant RFD air near the tornado. This surge also likely contributed to a displacement of the tornado from the storm updraft and to its demise. However, an RFDIS coupled with a convergent, near-neutrally buoyant and very potentially buoyant RFD flow field appeared to play an important role in the tornado rapid intensification stage. Tornado intensification may depend on an interaction of RFDIS convergence zones with a pre-tornadic circulation as seen in this model.



Tornadoes appear to die when RFD Internal Surges possess large, negative buoyancy as that air replaces more buoyant and more potentially buoyant RFD air surrounding the tornado. Also, it has been found that misalignment of the tornado and storm updraft may be factor. Clearly much more analysis of the RFD, FFD and mesocyclone datasets are needed.



While our knowledge of tornadoes has definitely increased and a clearer picture of the conceptual model has emerged, there remains some perplexing questions such as :

Atmospheric stability and helicity and the role of the tornado, how & why do tornadoes form? Tornadogenesis and tornado failure, the role of the RFD/FFD in tornado life cycle, what drives the RFD and is it related to a downward directed pressure gradient force? RFD origin and depth RFD characteristics – bouncy, vorticity, thermodynamics, microphysics.

Supercell Tornadic Storms Quiz

Quiz - 10 questions

Last Modified: May 12, 2015 at 09:36 AM

PROPERTIES

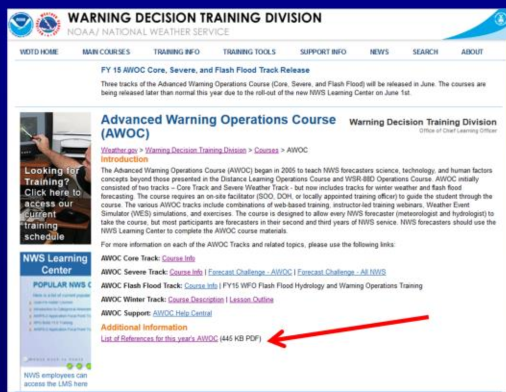
On passing, 'Finish' button:	Goes to Next Slide
On failing, 'Finish' button:	Goes to Slide
Allow user to leave quiz:	After user has completed quiz
User may view slides after quiz:	At any time
Show in menu as:	Single item

Edit in Quizmaker

Edit Properties

References

- See the reference page on http://www.wdtb.noaa.gov/courses/awoc



Please see the reference page for AWOC Severe Track IC1 at http://wdtb.noaa.gov/courses/awoc/index.html

Contact Information

Warning Decision Training Division
120 David L. Boren Blvd
Norman, OK 73072
(405) 325-2997

Brad Grant
bradford.n.grant@noaa.gov
405-325-2997